Selected Mission Architectures For The Terrestrial Planet Finder (TPF): Large, Medium, and Small

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ABSTRACT

Four teams incorporating scientists and engineers from more than 50 universities and 20 engineering firms have assessed techniques for detecting and characterizing terrestrial planets orbiting nearby stars. The primary conclusion from the effort of the past two years is that with suitable technology investment starting now, a mission to detect terrestrial planets around 150 nearby stars could be launched within a decade. Missions of smaller scale could carry out more modest programs capable of detecting and characterizing gas giant planets around tens of stars and of detecting terrestrial planets around the nearest stars.

Keywords: Terrestrial Planet Finder, planets, life, infrared, interferometer, coronagraph

1. TPF ARCHITECTURE STUDIES

In May 2000, four industrial/academic study teams began their investigations into architectures capable of performing the TPF mission of searching ~150 stars for earth-like planets and looking for signs of habitability or life around any planets detected in an initial survey. The teams, composed of scientists, engineers, and technologists, analyzed the capabilities of the different architectures and assessed the technical feasibility of the various concepts. In the first phase of the studies the teams were encouraged to explore the broadest possible range of ideas. In the second phase the teams carried out detailed analyses and trade studies on the most promising approaches for a TPF mission planned to start development around 2010.

Each of the teams defined their own approach for identifying and evaluating mission concepts. These concepts generally fell into three categories—the two largest categories are interferometers and coronagraphs, with most of the interferometers designed to detect the thermal infrared signal from planets, and most of the coronagraphs designed to detect the visible light reflected from the parent star. Within each of these two categories is a broad range of architectural concepts. A third category consists of architectures that are neither interferometers nor coronagraphs. In general, the mission concepts in the third category either cannot perform the full TPF mission of detection and characterization or are based on new technologies that are to be judged well beyond what is achievable in the next decade. A few examples of these are a separated spacecraft, Fresnel Lens coronagraph and a separated spacecraft occulter.

Table 1. TPF Architectures

Study Team	Architecture Class
Ball Aerospace	Shaped Pupil, Visible Light Coronagraph
	Classical Coronagraph
Boeing-SVS	Non-Redundant Linear Array (hyper-telescope)
	Apodized Square Aperture (partial study)
Lockheed-Martin	IR Interferometer (structurally connected and separated spacecraft)
TRW	Large IR Coronagraph
JPL	Re-examination of Separated Spacecraft IR Interferometer (TPF Book design)

During this period of the exploration of different concepts, the TPF Science Working Group (TPF-

SWG) agreed that both the thermal infrared and the visible-near infrared portions of the spectrum offered adequate information on the physical properties of planets, habitability, and the presence of life (biomarkers) so that technological readiness, not wavelength, should be the driving discriminant in choosing among various architectures[1,2].

After about seven months of work, each team provided a ranked list of their five preferred designs at the preliminary architecture review in December 2000. With additional input from the study teams and the aid of the TPF-SWG, the TPF Project selected from among the top ranked concepts to provide a diverse set of concepts for more detailed study (Table 1). Some of the contractors elected to investigate an additional concept at a lower level of effort. Between December 2000 and December 2001, the industrial teams made detailed studies of their selected architectures. After a review that included the TPF-SWG and an independent TPF Technology Review Board, the TPF Project selected a visible light coronagraph and an infrared coronagraph as being both capable of meeting TPF's scientific goals and being technically feasible with suitable investment. These options are described briefly below and in more detail in the *Summary Report on Architecture Studies for the Terrestrial Planet Finder*[3] and *The Terrestrial Planet Finder: A NASA Origins Program to Search for Habitable Planets*[4].

1.1. IR Nulling Interferometer

An IR nulling interferometer operating either on a fixed ~40-m structure or in a separated spacecraft configuration offers good performance. It can achieve the fundamental TPF goals of surveying nearby stars for Earths, carrying out a low spectral resolution characterization of the atmospheres, and searching amongst the brightest detected planets for ozone, an important biomarker (see references 3,4, and 5 for general summaries of the interferometric approach to TPF). In these designs, the angular resolution is of course limited by the length of the structure. The benefits of a single spacecraft system must, however, be weighed against the inability to resolve habitable zones subtending smaller angles.

Deciding between these two alternatives will require that important scientific, programmatic and technological tradeoffs be made over the next 3–4 years. The indefinite deferral of the Starlight flight mission makes it unlikely that a separated spacecraft technology demonstration mission can be operational before ~2010, thus calling into question the viability of a formation flying version of TPF ready for launch by 2015. If a flight validation of the formation flying interferometer is judged to be necessary prior to implementation on TPF, and if work over the next few years demonstrates that a structurally connected interferometer would be adequate to study a reasonable sample of stars, then NASA may choose to focus *at an early date* on this implementation of a nulling interferometer.

The issue of ancillary science is more challenging for the interferometer than for the coronagraph. While a cooled interferometer in space offers thousand-fold sensitivity advantages relative to ground-based systems, the angular resolution of a $\leq$40-m fixed boom system is modest compared to the Keck or VLT Interferometers. A separated spacecraft version of TPF would offer dramatic gains in both sensitivity and angular resolution for imaging science using baselines out to 1 km. It should be noted that extension to baselines longer than a few 100 m or operation on sources without a bright on-axis star (K~17 mag) to phase the interferometer would add significant complexity and cost to the system.

The largest area of technical risk for the infrared interferometers is not in the performance of the individual components but in the operation of the various elements as a complete system. No insurmountable problems were identified at the component or assembly level. Most of the required elements are either under development and making good progress or are reasonable extensions of technology being developed for missions and ground observatories that will be in place well before TPF needs them. But the overall complexity of this system, which incorporates the some of the most difficult aspects of SIRTF, NGST, SIM, and Starlight, cannot be overemphasized. Issues of integration and test will be very important. A major focus of TPF technology development in support of these architectures must be the development of system-level testbeds, simulators and integrated models that will provide the necessary insight into the problems associated with TPF performance at the system level.

1.2. Visible Telescope with a Coronagraph and/or Apodized Aperture

The primary focus of one team and the secondary priority of another team was on a visible light system using a large telescope along with a variety of techniques to reject diffracted and scattered starlight. A coronagraph incorporating a shaped pupil mask and a deformable mirror operating on a monolithic 4x10-m telescope shaped to fit into existing launch shrouds offers good performance and can achieve the fundamental TPF goals of surveying nearby stars for Earths, carrying out a low spectral resolution characterization of the atmospheres, and searching for an important biomarker, molecular oxygen, in the brightest planets detected.

Table 2. Time to Survey 150 Stars for 1 Epoch (days)

Architecture	Survey Time
Ball Coronagraph	15
Ball Shaped pupil	50
Boeing-SVS Apodized Square Aperture (ASA)	262
Boeing-SVS Non-Redundant Linear Array (NRLA)	55
Lockheed Martin (LMSS)	
40-m truss	40
Separated Spacecraft (Book Design)	106

The issue of ancillary science for this system is straightforward. The Ball and Boeing-SVS teams envision incorporating the coronagraphic capability as just one of a number of focal plane instruments. Traditional HST-like visible/UV instruments would offer greatly expanded scientific potential due to operation on a telescope with 20 times the collecting area of HST.

The areas of greatest technical risk for the visible coronagraph are in the development, manufacturing and implementation of the large, ultra-low wavefront error (WFE) primary mirror and components associated with the challenging requirements for starlight suppression. The TPF coronagraph requires a lightweight primary mirror three to four times the size of the HST mirror with a (corrected) wavefront error (WFE) over the critical mid-spatial frequencies of ≈1Å rms and a stability of ≤1 Å rms over the required integration time of several hours. The coronagraphs themselves are functionally simple, and although the demands for system performance are challenging, none are thought to be insurmountable. Work is in progress on many of the required elements, and in some cases (e.g., the high actuator density-deformable mirrors), is progressing very well. Studies are underway with regard to possible approaches for mirror fabrication. Mirror development will be a top priority over the next several years. A major focus of TPF technology development in support of this architecture is, and will continue to be, the development of system-level testbeds, simulators, and integrated models that will provide the necessary insight into the achievable levels of performance in the laboratory and problems associated with implementing this architecture in space for TPF.

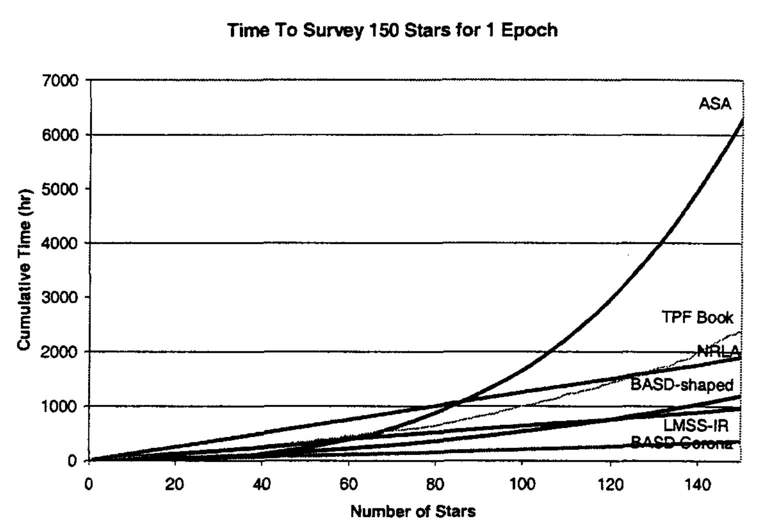

Figure 1. The cumulative time to search the habitable zones around a sample of 150 stars (1 epoch) is shown for 6 different architectures. The ASA performance could be improved with the implementation of a deformable mirror to further reduce scattered light.

1.3. Comparison of Observing Time Requirements

Figure 1 summarizes the time required to complete a survey of 150 stars. Because of the need to observe these stars at three epochs to confirm the detections and make a preliminary determination of orbital parameters, the full survey would take approximately 3 times longer. These estimates have not been optimized for observing strategies appropriate to particular designs or sky coverage through the year.

The Ball coronagraph completes the survey in the shortest time, but in all cases except the Boeing-SVS coronagraph, a three-fold redundant survey can be completed in less than 1 year. The performance of Boeing-SVS system could be made comparable to that of the Ball coronagraph by the addition of a deformable mirror to improve the ratio of planet light to residual starlight. The factor of two difference in speed between the two infrared interferometers is probably not significant given the large number of assumptions about instrumental and observational parameters.

A program of searching 150 stars along with follow-up observations to characterize ~50 planets in greater spectroscopic detail at a few days apiece could be carried out in half of a five-year mission. The remainder of the five-year mission duration could be spent on general astrophysics investigations or kept as a reserve against decreases in instrument capability or operational efficiency.

2. PRECURSOR MISSIONS TO DETECT GAS-GIANT PLANETS AND NEARBY EARTHS

The TPF-SWG considered the potential application of TPF technology to the study of gas-giant planets and was emphatic that detection and characterization of such planets was of great scientific interest in its own right. For example, Figures 2 and 3 show visible and mid-IR spectra of various gas giant planets. The appearance of the gas giants in our own solar system are quite distinct from one another and the physical properties and evolutionary history leading to those differences represent fundamental questions for our understanding of planets in general. In many cases, gas giants can be detected more easily than terrestrial planets, depending on wavelength region and orbital location. Advantages of direct detection of giant planets, particularly those on more distant orbits, include immediate and simple identification of multiple planets and planets on long periods that would be difficult to detect with radial velocities or astrometric techniques. In the long run, spectral or color information available from direct detection techniques could yield radius and mass estimates that might be accurate enough to distinguish between gas-giant and terrestrial planets, but verifying such an assertion will require dynamical and photometric data on a larger sample of objects than the nine planets in our own solar system.

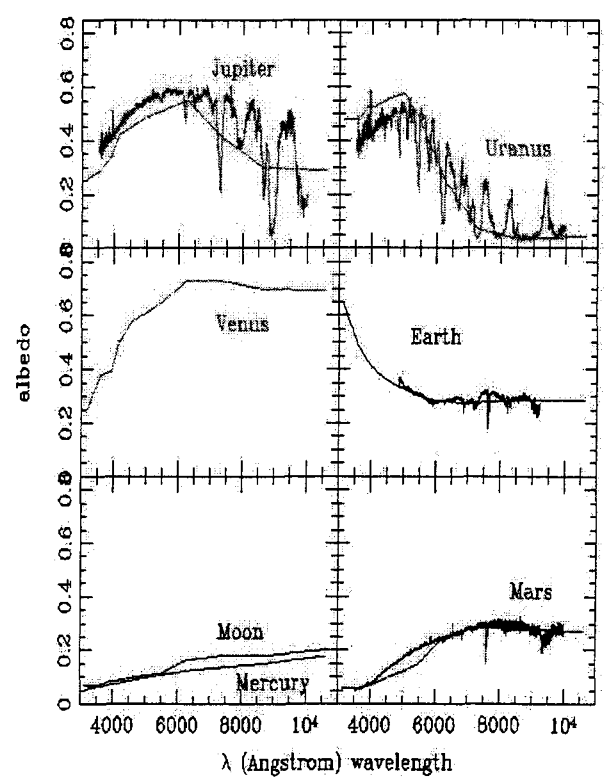

Figure 2. The visible spectra of planets in our solar system reveal a great deal of information on their physical properties (Traub, private comm.)

The TPF-SWG emphasized that a mission capable of studying a large number of giant planets and a small number of terrestrial planets (those within 8 pc) would be a scientifically credible and important mission[6]. Such a mission would also serve as a technological first step along the way to missions capable of finding and characterizing in greater detail more Earths around more distant stars. The case for a mission of smaller scope than the full TPF mission described in this report would be greatly bolstered if transit experiments, such as the Kepler[7] mission or by other means, were to determine that terrestrial-sized planets in the habitable zones of solar-type stars were a common occurrence[9], $\eta_\oplus \sim 1$. As described in their final reports, a number of the teams investigated smaller-scale yet scientifically meritorious missions that would potentially be less technologically challenging, lower in cost and risk, and ready to proceed into implementation before the full scale TPF (Table 3).

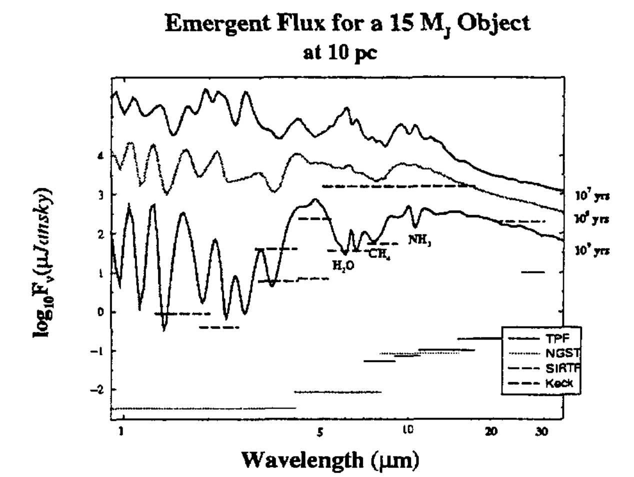

Figure 3. The infrared spectrum of giant planets offers a number of important spectral features observable at low resolution[8].

3. STRATEGY LEADING TO A FORMULATION PHASE BY 2007

TPF will be the next major mission in the Origins program following SIRTF, SIM and NGST with a launch date around 2015. In support of this schedule NASA will enter a 3~4 year period of intensive scientific investigation, design study and technology development leading to the selection of the final TPF architecture no later than mid FY 2006 in preparation for entering the formulation phase by FY 2007. During the pre-formulation phase, NASA has allocated $200M to support three main areas of activities: science, mission studies, and technology development:

- Approximately 10% of the total TPF budget will be allocated on an annual basis to support TPF preparatory science investigations and fellowships with the goal to understand better the nature and, if possible, the frequency of occurrence of Earthlike planets around other stars. These funds will be awarded through competitive processes such as NASA Research Announcements.

- JPL will perform detailed mission studies of "point designs" for the coronagraphic and interferometric versions of TPF. The products of these studies will be concepts similar in nature and utility to the NGST "Yardstick" design developed by GSFC in the early stages of NGST development.

Table 3. Potential TPF Precursors

Mission	Technology Benefit	Science Return
Starlight	Formation Flying Interferometry	None
IR Interferometer (9-m baseline, two 0.6-m mirrors)	Demonstrate IR nulling; precision, cryogenic structure	Detection of Hot Jupiters
IR Interferometer (20 m, 4 2-m mirrors)	Demonstrate IR nulling, precision, cryogenic structure	Jupiters, Nearest Earths (<8 pc)
Visible Coronagraph (2-m mirror)	Demonstrate visible coronagraph, apodized apertures	Low resolution spectroscopy of Jupiters to 25 pc
Visible Coronagraph (4-m mirror)	Demonstrate visible coronagraph, apodized aperture; fabrication of large telescopes	High resolution spectroscopy of Jupiters to 50 pc, Nearest Earths. Strong ancillary astrophysics

- The bulk of TPF funding will be targeted to developing the key technologies needed for both architectures. The goal will be to develop the critical technologies by the end of FY 2005 to the level required to assess their suitability for inclusion in a mission that would start around 2010. Technology development will be performed through a combination of efforts at JPL and major competed efforts in industry or at universities. Several major technology solicitations have already been executed or are in preparation. Following the selection of an architecture, the design will be refined and key technologies developed during the formulation phase. Additional insight into the scientific or technology issues will be gained from precursor missions such as SIRTF and Kepler as well as any other precursors.

4. INVOLVEMENT WITH INTERNATIONAL PARTNERS

The TPF Project has worked closely with other space agencies to lay the groundwork for future collaboration. In Europe, ESA has been studying the Darwin mission which is an nulling IR interferometer similar to the free flying interferometer studied in the US. Two years ago NASA and ESA each named scientists to serve on the science team of the other agency's project. A Letter of Agreement is pending between ESA and NASA to lay out plans for collaborative studies and ITAR-compliant technology development in support of the architecture downselect to take place in 2–3 years. This letter acknowledges the ultimate goal of a collaboration on a joint TPF/Darwin mission. Each agency will continue to have members on both science teams and will have semi-annual management meetings to ensure close coordination between the projects and agencies on technology plans, key decisions and project milestones. In addition to its contacts with ESA, the TPF Project has worked with the Inter-Agency Consultative Group (IACG) that advises NASA, ESA, the Japanese (ISAS) and Russian space agencies. The IACG has established a working group to advise all four agencies on the opportunities for additional collaborations.

5. CONCLUSION

As the technology matures and the opportunity to start the mission approaches, NASA and the science community will have to reach a consensus on the scientific performance in the areas of planet finding and general astrophysics needed to justify the mission. The present view on the importance of TPF's goals is well described in the NAS/NRC survey of astronomy and astrophysics (2001) which concluded[10]:

> *"Search for life outside of earth and, if it is found, determine its nature and its distribution in the galaxy...[This] is so challenging and of such importance that it could occupy astronomers for the foreseeable future."*

Some of TPF's observational capabilities will be affordable; others will have to be deferred to subsequent, still more capable missions. This judgment will demand increased knowledge about all aspects of the frequency, nature and evolution of planetary systems. The missions and investigations outlined above, including SIRTF, SIM, Kepler, and NGST, as well as ground-based activities will provide important scientific background. The technology program, if adequately funded, will provide the engineering basis for choosing a particular design and implementing it in a timely and cost-effective manner. At the end of TPF's pre-formulation phase, NASA, together with its potential international partners, will be prepared to address the challenge of looking for habitable planets and seeking signs of life beyond the Solar System.

ACKNOWLEDGEMENTS

The research described in this paper was performed at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. This work was supported by the TPF project. The author acknowledges valuable contributions from TPF Science Working Group and the contractor teams.

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